SELF-CALIBRATING INSTRUMENTED TOW CABLE

TO ALL WHOM IT MAY CONCERN:

BE IT KNOWN THAT ANTHONY A. RUFFA, employee of the

United States Government, citizen of the United States of

America, and resident of Hope Valley, County of Washington,

State of Rhode Island has invented certain new and useful

improvements entitled as set forth above of which the

following is a specification:

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3   **SELF-CALIBRATING INSTRUMENTED TOW CABLE**

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5   **STATEMENT OF GOVERNMENT INTEREST**

6   The invention described herein may be manufactured and used

7   by or for the Government of the United States of America for

8   governmental purposes without the payment of any royalties

9   thereon or therefor.

10

11   **BACKGROUND OF THE INVENTION**

12 **(1) Field of the Invention**

13   The present invention relates to arrays towed through the

14 water by vessels and more particularly to an improved tow cable

15 for the arrays in which the temperature at various radii of the

16 tow cable is measurable thereby self-calibrating the tow cable

17 to account for the heat-dissipation of the tow cable in order to

18 measure the temperature of the water surrounding the tow cable.

19 **(2) Description of the Prior Art**

20   In naval operations, an array is towed behind a vessel for

21 gathering information, such as the location of enemy vessels or

22 the depth of the ocean. A typical array comprises an exterior

23 hose wall fabricated from rugged, insulated material, and a

24 plurality of information gathering wires communicating with

1 acoustical sensors disposed within the protective hose wall.

2 The conducting wires or optical fibers of the towed array

3 transmit information via the tow cable to a microprocessor

4 within the vessel for a readout of gathered data.

5 In addition to transmitting information, the tow cable also

6 powers the array. Since the conducted power generates heat, the

7 conducted power impacts the temperature of the cable and the

8 water surrounding the cable. Further measurements that rely on

9 the surrounding water temperature such as a sound velocity

10 profile, can therefore be impacted by temperature variances

11 along the length of the tow cable. Since no segment of the tow

12 cable or only a minimal portion of the tow cable can be accessed

13 on surface vessels, an accurate temperature measurement at

14 different points along the length of the tow cable is difficult

15 to discern after the tow cable is deployed or "let out" from the

16 winch of the array handling system.

17 In the art, various methods and devices are employed to

18 measure the temperature of the tow cable and the surrounding

19 water column. In Seaman et al. (U.S. Patent No. 6,147,931), an

20 apparatus for providing a temperature profile of a towed sonar

21 array is disclosed. In the cited reference, the tow cable for

22 the array comprises a central cable and a protective outer

23 jacket. Thermistors are disposed at spaced positions along the

24 outer jacket and connect to conductors embedded in the outer

1   jacket. The conductors terminate onboard ship to provide

2   continuous signals representing temperatures at various ocean

3   depths.

4   While thermistors can be positioned along the length of the

5   tow cable to determine the temperature of the water, this use of

6   thermistors is limited in its practical application. In a first

7   example, using a high number of thermistors is impractical for a

8   tow cable that can be as long as 8000 feet. Since each

9   thermistor requires its own pair of conductors, the high number

10 of thermistors can significantly increase the tow cable diameter

11 over the length of the tow cable. In a second example, the

12 technology of the cited reference is not easily transferable to

13 the tow cable because of the strain encountered by the tow cable

14 at the curvature of the cable to the winch of the towed array

15 handling system. A separate protective band for the thermistor,

16 as disclosed by the cited reference, is susceptible to

17 detachment during repeated use of the tow cable such that the

18 thermistor is easily exposed to these strains with the result of

19 inaccurate information gathering if the thermistors are damaged.

20   In Yamaguchi et al. (U.S. Patent No. 5,198,662), a

21 measuring system measures temperature distribution in water

22 using an optical fiber. In the cited reference, the optical

23 fiber is positioned in a central pipe sealed by filler material.

24 Although, the optical fiber positioned in this manner can

1 determine the temperature of the proximate water column, the

2 positioning of optical fibers as temperature sensors can be

3 improved.

4   An improvement to the positioning of sensors for measuring

5 temperature would be the ability to gather measurements at

6 varying radii of the cable rather than only at the center of the

7 cable. Gathering measurements at varying radii along a common

8 vector from the center of the tow cable increases the accuracy

9 of temperature measurements of the surrounding water column.

10

11 **SUMMARY OF THE INVENTION**

12   Accordingly, it is a general purpose and primary object of

13 the present invention to provide a tow cable in which

14 temperature measurements at various radii of the tow cable are

15 attainable thereby self-calibrating the tow cable to account and

16 correct for the heat-flow in the radial direction in order to

17 measure the temperature of the water surrounding the tow cable.

18   It is a further object of the present invention to provide

19 a tow cable in which temperature measurements at various radii

20 of the tow cable and along a common vector extending from a

21 center of the tow cable are attainable.

22   It is a still further object of the present invention to

23 provide a tow cable which compensates for the strain encountered

1   by the tow cable especially at the winch of the towed array

2   handling system.

3   To attain the objects described, there is provided a tow

4   cable in which the temperature of the tow cable is measured by

5   the use of multiplexing capability intrinsic to optical fibers

6   in which the optical fibers are positioned at the center of the

7   tow cable and separately wound as part of two layers of

8   surrounding strength wires. During measurement, light signals

9   are emitted from a multiplexer aboard the towing vessel to

10   positions along the optical fibers in which the positions are

11   intersections of a vector extending radially from a longitudinal

12   axis to an outer surface of the tow cable. The returning light

13   signals from the positions provide measurements that in

14   conjunction with a data processor further provide measurement of

15   the outer boundary temperature of the tow cable. The outer

16   boundary temperature of the tow cable is determinant of the

17   surrounding water column temperature. Sound velocity profiles

18   are easily derived from the water column temperature by methods

19   known to those skilled in the art.

20   In the manufacture of the tow cable, a steel strength

21   member wire is substituted in one armored layer of the tow cable

22   and another steel strength member wire is substituted in another

23   armored layer. The steel strength member wires are substituted

24   with armored optical fibers or bendable stainless steel tubing

1 encompassing an optical fiber. In an additional manufacturing

2 step, an optical fiber is positioned within stainless steel

3 tubing as the center of the tow cable.

4 The above and other features of the invention, including

5 various and novel details of construction and combinations of

6 parts will now be more particularly described with reference to

7 the accompanying drawings and pointed out in the claims. It

8 will be understood that the particular devices embodying the

9 invention are shown by way of illustration only and not as the

10 limitations of the invention. The principles and features of

11 this invention may be employed in various and numerous

12 embodiments without departing from the scope of the invention.

13

14 **BRIEF DESCRIPTION OF THE DRAWINGS**

15 A more complete understanding of the invention and many of

16 the attendant advantages thereto will be readily appreciated as

17 the same becomes better understood by reference to the following

18 detailed description when considered in conjunction with the

19 accompanying drawings wherein:

20 FIG. 1 depicts an arrangement view of the tow cable of the

21 present invention secured to a towing vessel and a sensor array;

22 FIG. 2 depicts a cross-sectional view of the location of

23 the optical fibers in the tow cable of the present invention

24 with a number of strength and conducting wires of the tow cable

1   removed for purposes of clarification and with the view taken

2   from reference line 2-2 of FIG. 1;

3   FIG. 3 depicts a cross-sectional view of the location of

4   the optical fibers in the tow cable of the present invention

5   with a number of strength and conducting wires of the tow cable

6   removed for purposes of clarification and with the view taken

7   from reference line 3-3 of FIG. 1;

8   FIG. 4 depicts a cross-sectional view of the intersecting

9   radial location of the optical fibers with the strength wires

10 and conducting wires of the tow cable removed for purposes of

11 clarification and with the view taken from reference line 4-4 of

12 FIG. 1; and

13   FIG. 5 depicts a perspective view of the tow cable of the

14 present invention in which the optical fibers are wound at a

15 helical angle with the strength wires and conducting wires of

16 the tow cable removed for purposes of clarification.

17

18   **DESCRIPTION OF THE PREFERRED EMBODIMENT**

19   Referring now to the drawings wherein like numerals refer

20 to like elements throughout the several views, one sees that

21 FIG. 1 depicts an arrangement view including the tow cable 10 of

22 the present invention let out from a winch 12 of a vessel 14 in

23 which the tow cable tows an acoustic sensor array 16 through the

24 ocean 18. The tow cable 10 powers the sensor array 16 and

1 transmits measurement data from the sensor array to a

2 multiplexer/demultiplexer 20 with data processing capability or

3 transmits measurement data to other data processors known to

4 those skilled in the art.

5 As shown in the cross-sectional view of FIG. 2, the double-

6 armored tow cable 10 includes a centrally located section 30,

7 including at least one optical fiber 32 contained in a stainless

8 steel tube surrounded by electrical conductors 34 (for

9 transmitting power and signals). The optical fiber 32

10 preferably extends along a longitudinal axis of the tow cable

11 10; however, the optical fiber may extend parallel and helical

12 to the longitudinal axis of the tow cable.

13 Surrounding the central section 30 are two armored layers

14 36 and 38 of strength wires 39. An optical fiber 40 encompassed

15 by another stainless steel tube 41 or an armored optical fiber

16 42 of FIG. 3 replaces one of the strength wires 39 helixed

17 around the section 30 as the first armored layer 36. An optical

18 fiber 46 of FIG. 2 encompassed by another stainless steel tube

19 48 or an armored optical fiber 50 of FIG. 3 replaces another of

20 the strength wires 39 helixed around the first armored layer 36

21 as the second armored layer 38. The number of steel strength

22 wires 39 are shown in FIG. 2 and FIG. 3 for comparison and

23 illustrative purposes wherein the actual number would be much

24 larger and arrangement of the steel strength wires would vary.

1   As shown in FIG. 4, each of the armored optical fibers 42

2   and 50 intersects a vector 52 extending from the optical fiber

3   32 of the central section 30. The vector 52 extends radially

4   from a longitudinal axis 54 of the tow cable 10 such that the

5   measurements derived from the group of optical fibers 32, 42 and

6   50 are localized. The armored optical fibers 42 and 50 also

7   intersect additional vectors extending similar to the vector 52

8   with the additional vectors at various lengths of the tow cable

9   10 such that the temperature of the water column at various

10   points along the tow cable is measurable. Measurements are

11   derived from the group of optical fibers 32, 40 and 46 in a

12   similar manner as the optical fibers of FIG. 4 with a similar

13   positioning of the optical fibers 32, 40 and 46 as the optical

14   fibers of FIG.4.

15   Furthermore, the armored optical fibers 42 and 50 replace

16   strength wires 39 that are wound around the longitudinal axis 54

17   at a helical angle θ depicted in FIG 5. The optical fibers 40

18   and 46 are similarly wound around the longitudinal axis 54 as

19   the optical fibers 42 and 50 shown in FIG. 5. The helical angle

20   θ is approximately 20 degrees; however, the helical angle is

21   based upon manufacturer's specifications (i.e.: the helical

22   angle may decrease for larger tow cables). The placement of the

23   armored optical fibers 42 and 50 at the helical angle θ to the

1 longitudinal axis 54 is chosen to reduce the strain of the tow

2 cable 10 at the large bending of the tow cable 10 encountered at

3 the winch 12.

4 In a data-gathering operation during the towing of the

5 array 16, the multiplexer/demultiplexer 20 emits optical pulses

6 of light through the optical fibers 32, 42 and 50 of FIG. 3 as

7 an example. The multiplexer/demultiplexer 20 also receives

8 backward scattered light from the optical fibers 32, 42 and 50

9 resulting from the emitted optical pulses of light. The back-

10 scattered light has a component not shifted in frequency (due to

11 Rayleigh scattering) and a component shifted in frequency (due

12 to Raman scattering).

13 In terms of the wavelength distribution, the back-scattered

14 light includes Rayleigh scattered light having the same

15 wavelength (λ_0) and the Raman scattered light deviated $6\Delta\lambda$ from

16 the incident light. The Raman scattered light deviated $+\Delta\lambda$ from

17 λ_0 is referred to as Stokes light while the Raman scattered light

18 deviated $-\Delta\lambda$ from λ_0 is referred to as anti-Stokes light.

19 The location of detection data is obtained from the tow

20 cable 10 by denoting the relation between the time (t) elapsed

21 from the incidence of optical pulses emitted and the intensity

22 of light detected by the multiplexer/demultiplexer 20. The data

1 denoting the detected light intensity is inputted in a data

2 processing portion of the multiplexer/demultiplexer 20.

3   Since the velocity of light in optical fibers is known, the

4 time (t) that elapsed from the incidence of the optical pulses

5 to the detection of a signal represents the distance from the

6 end of the optical fibers.

7   The Raman scattering effects can be used to derive the

8 temperature (T); this is well-known to one skilled in the art.

9 The time of arrival processing described above (and also well-

10 known in the art) determines the location of each temperature on

11 the optical fiber.

12   Since the distance of emitted light can be obtained as

13 stated above, the vector 52 of FIGS. 4 and 5 can also be

14 established at a distance from the end of the tow cable 10.

15 Because of the helixing of the optical fibers 42 and 50 along

16 the tow cable 10, the distances of emitted light for these

17 optical fibers is slightly higher at the vector 52 and therefore

18 the measurements based on these distances should be compressed

19 multiplexer/demultiplexer 20 with data processing capability and

20 accounted for at the vector 52. For example, the distance of

21 emitted light at the optical fiber 32 would be five hundred feet

22 while the distances at the optical fibers 42 and 50 may be five

23 hundred and twenty-five feet and five hundred and fifty feet

24 respectively, depending on the helix angle.

1   Once a distance is established and a temperature is

2   measurable at the optical fibers 32, 42 and 50, the boundary

3   condition of the tow cable 10 is measurable with a substantial

4   degree of accuracy. The water temperature T_0 at the water column

5   (of the ocean 18 or other surrounding fluid condition) is at or

6   proximal to the boundary condition. Specifically, the heat

7   going into the surface, q, at the radius r_3 of the tow cable 10

8   is resolved by the equation:

9     $$q = KA\frac{\partial T}{\partial r}(r_3) \cong KA\left(\frac{T_3 - T_2}{r_3 - r_2}\right)$$ assuming that $\nabla^2 T = 0$ in the second

10   armored layer 38.

11   In the equation, the thermal conductivity is K; A is the

12   circumferential area at the radius r_1 and $\dfrac{\partial T}{\partial r}$ represents the

13   temperature gradient measured at the radius r_2 and the radius r_3

14   (r_3=0) of FIG.4.

15   Solving for Laplace's equation for heat conduction using

16   the cylindrical coordinates intrinsic to the tow cable 10 and

17   assuming axisymetric temperature distribution:

18    $$\nabla^2 T = \left[\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2}\right] = 0$$

19   the temperature T of the surrounding water column at a length z

20   of the tow cable 10 is resolvable.

12

1   The water temperature T is reflected by example as T_0 in

2   FIGS 2 and 3. It is found by fitting the solution to the

3   temperatures: T_1 at the optical fiber 50 (alternatively the

4   optical fiber 46 in FIG. 2); T_2 at the optical fiber 42

5   (alternatively the optical fiber 40) and T_3 at the optical fiber

6   32. If the temperature is measured at three radial locations

7   and if the temperature is assumed axisymmetric in nature, the

8   temperature of the tow cable 10 can be determined by solving

9   Laplaces's equation with T_0 and T_3 as boundary conditions with an

10   effective conductance representing the cable material.

11   Since T_0 is unknown, the problem is solved for a range of

12   values of T_0, and then the value of T_0 is chosen that best fits

13   the measured temperatures T_1 and T_2. Since the problem is

14   linear, a look-up table can be pre-computed and stored so that

15   Laplace's equation does not have to be solved in real time. As

16   a result, the temperature T_0 of the surrounding water column at a

17   length z along the tow cable 10 is resolved. Fitting to two

18   temperatures T_1 and T_2 in a least squares sense minimizes error

19   compared to fitting to only one interior temperature. Also,

20   this accounts for cable heating in the center, which is

21   reflected by the temperature T_3.

22   Thus by the present invention its objects and advantages

23   are realized and although preferred embodiments have been

1   disclosed and described in detail herein, its scope should be

2   determined by that of the appended claims.